"Improving one's touch" and more
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Abstract

Gordon & Cooper (1975) have described an interesting tactile phenomenon. The orientation of undulations on the surface of an object can be detected more accurately when a person moves an intermediate paper over the surface than when the bare fingers are used. Counter to a prediction derived from Gordon and Cooper's explanation of their results, the present studies show that the apparent roughness of a surface increases when a similar manner of touching is used. The first two experiments confirm the latter observation. To explain the alteration in perceived roughness (and more tentatively, Gordon and Cooper's own findings), it is proposed that surface roughness (and undulations) are masked by shear forces applied to the skin. Two informal tests and a third experiment support this interpretation. Alternative explanations and a practical application for the blind are also considered.

In 1975, Gordon & Cooper described an intriguing tactile phenomenon. A person may detect the orientation of surface undulations better when moving a thin, intermediate paper across a surface than when the bare fingers are used. Although it is unlikely this phenomenon has ever been subject to scientific investigation, it has long been used by craftsmen and auto body shops to examine the finish on molded surfaces and automobiles.

The laboratory demonstration used by Gordon & Cooper was as follows. A steel block was produced with its upper surface ground smooth, and a central, raised rectangular strip, 3 mm wide and .0127 mm high. The surface was covered with a smooth card (0.5 mm thick), thereby producing a gradual undulation across the central strip. Accuracy in identifying the orientation of this undulation was approximately 60% when examined with the bare fingers, increasing to 80% when another piece of paper was moved with the fingers across the undulation. By way of explanation, Gordon & Cooper point out that there are several types of receptors in the skin which respond to mechanical deformation (Talbot et al, 1968). When touching an undulating surface, it is possible that "... a highly sensitive system such as that associated with light pressure, may interfere with the input from deeper receptors, the response to roughness thus masking the

response to more gradual surface changes. The effect of placing material under the fingers may be to reduce the masking, thus allowing the appropriate input to be used in detection" (Gordon & Cooper, 1975).

Given the validity of their explanation, Gordon and Cooper may make a further prediction about the perceived roughness of surfaces felt with and without an intermediate paper. The investigators imply that the paper serves to reduce the masking of the more gradual surface changes ("undulation") by reducing "roughness", by which they mean, presumably, the higher-frequency irregularities on the same surface. The physical reduction in surface roughness effected by the intermediate paper may of course result in no change whatsoever in perceived roughness (relative to that experienced when touching with bare fingers). But should a change occur, Gordon and Cooper must predict that the perceived roughness of their surface, or any surface for that matter, will decrease when the paper is used. An increase in apparent roughness would constitute evidence against the investigators' explanation.

Experiment 1 tested the deduction one would make on the basis of Gordon and Cooper's explanation. Subjects judged (by magnitude estimation) the roughness of a set of textured surfaces twice, once with bare fingers, and once using an intermediate paper.

Experiment 1

Method

Subjects. Twenty-five introductory psychology students participated. All were right-handed (as defined by writing hand), and naive as to the purpose of the experiment.

Apparatus and stimuli. Each of seven wooden plates, 15 x 15 cm, was covered with sandpaper of a single grit value, 40, 50, 60, 80, 100, 120 or 150. (Grit refers to the number of openings per inch in the sieve used to produce the sandpaper. Thus, as grit value increases, the size of particles necessarily decreases.) The plates were then covered with writing paper (Dompak 9(M)) to prevent any particles from being dislodged. The intermediate paper (the same paper as the covering just mentioned) used on half the trials was approximately 22 x 28 x .0004 cm. In all three experiments, subjects were blindfolded. Head phones were worn, and white noise was introduced into the room through a loudspeaker to mask the touch-produced sounds.

Procedure. The subject and experimenter sat opposite each other at a table. The experimenter placed the squares, one at a time, in front of the subject, and indicated whether the subject should examine the surface with ("paper"

condition) or without ("no-paper" condition) the intermediate paper. The middle three fingers of the right hand were used. Subjects were told to maintain the same force throughout the experiment, and to feel the surfaces lightly and for a short time. However, no exact time limit was imposed. Subjects were initially presented with two practice plates which were not part of the stimulus series, each felt with and without the paper.

A modified magnitude estimation procedure was used, the details of which are described in Lederman & Taylor (1972). Subjects were instructed to assign any positive, non-zero number (decimal, fraction, or whole number) in proportion to the roughness of the surface. Each surface was judged relative to the one immediately preceding it. Thus, if a subject called a surface "10", and the next surface felt twice as rough, s/he assigned the number "20". Neither standard nor modulus was used.

Experimental design. A repeated measures, 3-factor design was used. Each subject judged the roughness of seven surfaces in both paper and no-paper conditions. The presentation order of the 14 experimental trials (as well as the set of four practice trials) was randomized. The entire set was then repeated using a different random order.

Results

An analysis of variance performed on the logarithmically transformed data revealed that the effects due to grit and mode of touching were both highly significant ($F=41.6$, $p<.0001$; $F=36.4$, $p<.0001$, respectively); none of the other effects or their interactions was significant. The results are shown in Fig. 1. Perceived roughness (magnitude estimates) is plotted as a function of grit value for both paper and no-paper conditions (log scales). It should be recalled

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Insert Fig. 1 about here

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that all surfaces were tightly covered with a sheet of paper. In contrast to the no-paper condition, however, the paper condition involved an additional sheet of paper which was moved with the hand over the papered-surfaces. Each point represents the geometric mean of 50 observations. Roughness tends to decrease with increasing grit value (and thus, decreasing particle size); furthermore, roughness is greater for all surfaces when the paper is used.

Discussion

It is evident that touching a surface by moving an intermediate paper with the fingers alters the perceived roughness of the underlying surface, but in a direction opposite to Gordon & Cooper's prediction. The apparent roughness of a surface is heightened when one moves an intermediate paper across that surface.

How might the results of the first experiment be explained? To judge the roughness of a surface, there must be relative motion between that surface and the hand. This means that as the hand is moved, both downward (normal) and lateral (shear) forces are applied to the skin of the fingertip. What role might these forces play in the perception of tactile roughness?

Previous experimental work (e.g. Lederman & Taylor, 1972) points to the importance of normal forces in the perception of roughness: perceived roughness grows with increases in the force applied normally to the skin. Normal forces also play a significant part in the theoretical work on tactile roughness (Taylor & Lederman, 1975).

The effect of shear forces, however, has not been considered in our work previously. It is possible that shear might interfere with or mask the effects of the relevant normal forces on perceived roughness.

According to what will be called a "reduced-shear" interpretation, the intermediate paper used in Expt. 1 serves to decrease shear, and thus the amount by which the roughness signal is masked. It may be that the proposed analysis relates to Gordon & Cooper's finding as well, since detecting the orientation of a single raised undulation (like a cluster of tiny bumps) similarly involves the application of both normal and shear forces to the skin.

There is at least one important difference between the two experiments, however. Expt. 1 deals with the magnitude of roughness sensations, whereas Gordon & Cooper's study addresses itself to the accuracy of orientation detection. Since their task involves not simply undulation detection, but also detection of the orientation of this undulation, we should consider the issue somewhat further. It is possible that Gordon & Cooper's subjects were performing close to threshold when they used their bare fingers. Errors in orientation might have resulted from errors in detecting the presence of the undulation. Reduced masking in the paper condition might serve to improve accuracy in detecting the orientation of the undulation by raising the deformation signal above detection threshold. If this were correct, one could expect to find a height beyond which judgments were similar, both with and without the paper. In their article, the authors only reported percent detection of the 13μ

ridge. However, all of the higher-ridged surfaces used in the practice sessions yielded similar (near perfect) performance, both with and without the paper (Gordon, 1976). Without further measurement and experimentation, it is difficult to describe the nature of the stimulus precisely, or to estimate the appropriate threshold value for undulation detection. For now, I can only speculate that the increased accuracy of orientation may be a threshold-related phenomenon. If this is true, the reduced-shear explanation may apply to Gordon & Cooper's findings as well. However, the proposed application is strictly tentative at this time.

Experiment 2

As an alternative to the reduced-shear interpretation, one may argue that subjects press harder in the paper condition to obtain precise control over the motions of the intermediate paper. Earlier work (Lederman & Taylor, 1972) has shown that perceived roughness does increase with increasing force, and downward force was not controlled in Expt. 1. If subjects actually did press harder in the paper condition, they may have judged the surfaces to be rougher than in the no-paper condition.

A control experiment was therefore carried out to determine whether the phenomenon would still occur when downward finger force was held constant across the paper/no-paper conditions of touching.

Method

Subjects. Thirty introductory psychology students participated. Once again, all defined themselves as right-handed, and had no previous experience in tactile perception experiments.

Apparatus and stimuli. A balance apparatus was used to control force (for details, see Lederman & Taylor, 1972). It was designed along the lines of a classical balance scale, with weights at one end of the balance arm and the stimulus surfaces at the other. The subject was instructed to move his/her fingers across the surface with enough force to maintain the balance arm steady and level. Three force conditions were used, 40, 120, and 290 gm (called "light", "medium", and "heavy", respectively), applied with the middle three fingers of the right hand. The forces were chosen to cover a "comfortable" range, i.e. one which the subjects were likely to use when force was not controlled. Four of the (paper-covered) sandpaper stimuli from Expt. 1 were used in this experiment. They were 40, 80, 100 and 150

grit. As in Expt. 1, a piece of writing paper (22 x 28 x .0004 cm.) was used in the paper condition.

Procedure and design. The procedure was similar to that used in Expt. 1. Subjects made magnitude estimates of the roughness of four stimuli in paper and no-paper conditions with each of three forces. As practice, 60 (with low force) and 120 (with heavy force) grit surfaces were examined, with and without the intermediate paper. The presentation orders of practice and experimental trials were both randomized. Each subject repeated the experimental set of 24 trials once.

Results

The magnitude estimates were logarithmically transformed, and an analysis of variance performed. A completely crossed design was used, the factors being replications, grit, mode of touching and finger force. Grit, mode of touching, and force effects were all highly significant ($F=121.2$, $p<.0001$; $F=21.6$, $p<.0001$; $F=28.1$, $p<.0001$, respectively). Grit x mode of touching and force x mode of touching were also statistically significant ($F=3.07$, $p=.03$; $F=10.1$, $p=.0004$, respectively). Replications x grit x mode of touching and replications x force effects were both significant, but negligible when compared with the factors of interest here.

Insert Figures 2a, b, & c about here

The results are shown in Figs. 2a, b and c. Geometric means of the roughness estimates are plotted as a function of grit for the paper and no-paper conditions (log scales). Fig. 2a represents the light force condition, and Figures 2b and 2c, the medium and heavy force conditions, respectively. As in Expt. 1, perceived roughness tended to be greater in the paper than in the no-paper condition. However, when light force was used, the effect was negligible, although it did tend in the predicted direction. Multiple comparisons of the paper vs no-paper means for each of the three force conditions (Scheffe's method) indicated no significant difference in perceived roughness when the light force was used ($F=0.797$, $p>.10$); apparent roughness was significantly greater in the paper than in the no-paper condition when medium and heavy forces were used ($F= 63.6$, $p<.01$; $F= 69.8$, $p<.01$, respectively). A final test of the paper/no-paper difference in the medium versus heavy force conditions failed to show significance.

Discussion

It would appear that the increased roughness which occurs when an intermediate paper is used cannot be explained by the suggestion that people press harder. There is, however, a lower limit to the effect.

The average difference between the means for the paper and no-paper condition was .13 log units for both medium and heavy forces. In Expt. 1, the average difference was .07 log units. Why the effect is almost twice as large when force is controlled as when it is not, is unclear at this time. Perhaps some subjects in Expt. 1 chose to use very light forces. From the results of the low force condition in Expt. 2 (mean difference between paper and no-paper conditions= .01 log units), one would then deduce that averaging across subjects in Expt. 1 would reduce the size of the effect.

Evaluation of the Reduced-Shear Interpretation

Informal tests

There are two informal tests of the reduced-shear explanation which the reader may try for him/herself. Place a thin piece of paper over a surface, and move the fingers

over the sheet without moving the paper. The surface will feel smoother than when both paper and fingers move across the surface. The reduced-shear explanation predicts this difference in apparent roughness: when the paper is immobile, shear along the skin is increased, and thus the amount of masking as well. Next, move the fingers back and forth across the surface, again with the piece of paper underneath. This time, however, move the paper in a direction other than the one in which the fingers are moving. The surface will feel a little smoother than when the surface is felt through the paper moving with the fingers. This perception would also be predicted by the reduced-shear explanation, since once again shear between skin and surface has been increased when the skin moves relative to the paper. Both these demonstrations then provide informal support for the reduced-shear interpretation.

Formal test

The following experiment provides a more formal evaluation of the reduced-shear interpretation.

Experiment 3

In Expt. 3, shear forces were directly manipulated. Three levels ("low", "medium" and "high") of skin shear were used. The reduced-shear explanation predicts that the perceived roughness of each stimulus should be highest in the low shear condition, followed by the middle, and high shear conditions of touching. As will be seen, the predictions were clearly confirmed.

Method

Subjects. Thirty-five students from an introductory psychology class at Queen's University participated. All called themselves right-handed, and were experimentally naive.

Stimuli. For all shear conditions, each of four surfaces was produced by placing a single layer of spherical, glass beads[1] (of a given diameter range) on a relatively smooth base. A set of nested testing sieves was used to separate the spherical particles into four nominal sizes. The top-to-bottom order in which the sieves were nested was determined by decreasing aperture size (600, 425, 300 and 212 μ). Unsorted particles were placed in the top sieve. When the apparatus was vibrated, the beads

distributed themselves throughout the screens according to size, the smallest beads reaching the lowest tray. A given sieve therefore contained all beads which passed through the larger apertures of the tray immediately above, but were too large to pass any further. Accordingly, the unit of measure of bead size, i.e. nominal aperture width, actually describes a range of diameters, the lower end referring to the nominal aperture size of the sieve containing the beads, the upper end referring to the larger aperture value of the sieve immediately above it in the series. To obtain only the most spherical beads in each of the four categories, the beads were rolled down a gently sloping piece of glass. The most spherical particles rolled to the bottom; those which remained at some point along the glass were less perfectly spherical, and therefore discarded.

In the "high shear" condition, the beads were firmly attached to the base, and the "surfaces" thus produced were tightly covered with a double layer of tissue paper. (The double layer was required to maintain the same thickness of paper between skin and beads in all three experimental conditions.) During a high shear trial, the subject moved his/her fingers over the (double-layered) covered beaded surface. In the "medium shear" condition, the subject felt the same four surfaces, but this time moved the top layer of tissue paper (15.25 x 15.25 x .0001 cm., glossy side down)

with the fingers across the single-papered, beaded surface. The medium and high shear conditions were much like the paper and no-paper conditions, respectively, of Expts. 1 and 2. In the "low shear" condition, we used the same beaded surfaces, only the beads were allowed to roll freely. The subject moved a double layer of tissue paper (15.25 x 15.25 x .0002 cm., glossy side down) over the particles. Due to the spherical nature of the beads, only forces normal to the paper will be applied. Hence, there can be no shear (theoretically) on the paper moving over the beads, and consequently none on the skin, which is stationary relative to the paper. Subjects were unaware that they were feeling loose particles, and had no difficulty in judging the roughness of these somewhat unusual "surfaces".

Although it was not possible to measure shear directly, a method was devised to obtain some idea of the relative amounts of shear force produced in the three shear conditions. Basically , the method involved maintaining a constant finger force normal to a given surface, and determining the lateral force required to begin moving the surface underneath the static finger in each of the three shear conditions[2]. The measurements indicated that the greatest shear was produced in the high shear condition, followed by the medium and finally, low shear conditions. The three shear values were separated by approximately equal

amounts. Thus, the intended manipulation of shear appeared to be achieved.

Experimental procedure and design. The surfaces were arranged on a "lazy-Susan" tray so that the experimenter could quickly present the stimuli, one at a time, without disturbing the loose-bead surfaces used in the high shear condition. Subjects were told to feel the surfaces lightly with their middle three fingers. No time limits were set. In this experiment, judgments of roughness were made relative to a standard surface/shear condition (the 600 μ surface presented in the medium shear condition), called "10". The standard was presented at the beginning of each set of 12 trials. Each subject made roughness estimates in all 12 surface/shear conditions. The order of presentation was randomized, and the set of 12 trials repeated by each subject. At the beginning of the experiment, subjects were given three practice trials, with the 600, 425, and 212 μ surfaces presented in the low, medium and high shear conditions, respectively.

Results

The data were handled as before. A two-factor, completely crossed analysis of variance was used to examine the results. Both bead size and shear effects were highly

significant ($F=123.97$, $p<.0001$; $F=27.93$, $p<.0001$, respectively); the interaction of bead size with shear was not. The pattern of the data may be seen more closely in Figure 3. Geometric means are plotted as a function of nominal sieve-aperture width for each of the three shear conditions (log scales). The experimental predictions of

Insert Fig. 3 about here

the reduced-shear interpretation have been clearly confirmed. Perceived roughness of each surface was greatest in the low shear condition, followed by the medium and lastly, the high shear conditions of touching.

General Discussion

Expts. 1 and 2 show that when an intermediate paper is used, surfaces feel rougher than when the bare fingers are used alone. These results question the validity of the explanation Gordon and Cooper offered for the improvement they found in identifying the orientation of an undulation when an intermediate paper was similarly used.

An explanation of the heightened roughness phenomenon demonstrated in Experiments 1 and 2 has been proposed. It is suggested that lateral (shearing) forces acting on the skin normally mask the signal for roughness, produced in part by downward (normal) forces. When the intermediate paper reduces the shear forces, the amount of masking also diminishes. The result is an increase in apparent roughness relative to that experienced with the bare fingers.

Cussler, Zlotnick, & Shaw (1977) have shown that the perceived smoothness of liquids varies inversely with the shearing force. If, as they have assumed, smoothness is reciprocally related to roughness (Stevens & Harris, 1962), their data run counter to those reported here. The authors actually attempted to relate earlier work of mine (Lederman, 1974), reporting the perceived roughness of grooved metal plates, to shearing forces which they calculated theoretically. However, they incorrectly interpreted groove width (the factor I found most affected apparent roughness) to be equivalent to "d", the average diameter of points of contact. One wonders therefore whether the authors incorrectly used groove width specifications from my 1974 paper as values for "d", when estimating the shear forces. As the authors do not specify which experiment in the 1974 paper they obtained their data from, and since none of my experiments have as few data points as reported in the

Cussler paper, it is impossible to consider the work or its implications further here.

Both of the informal demonstrations and Expt. 3 lend support to the reduced-shear interpretation. In each condition in which shear was reduced, the apparent roughness increased (relative to the higher shear condition). At a sensory physiological level it is not yet known whether primary afferent units (for further discussion, see Vallbo & Johansson, 1977) ending in the skin of the fingertip code the application of normal and shear forces. Single-cell recording of responses by these receptors is necessary to determine conclusively whether any of these units, either singly or in some combination, can perform the task required by the reduced-shear interpretation. Further speculations on the receptor coding involved in the heightened impressions of roughness reported in this paper are presented elsewhere (Lederman, 1978).

The reduced-shear explanation may relate to Gordon and Cooper's findings too, if one were able to demonstrate that the difference in accuracy of discriminating the orientation of an undulation was in effect simply determined by a corresponding difference in the accuracy with which the presence of that undulation was detected. Although the idea seems plausible, there are a number of questions which must be answered before one can attempt to apply the

reduced-shear interpretation. Therefore, the application to Gordon and Cooper's finding remains tentative at this stage.

The results of the present studies are also of consequence for any general explanation of tactile roughness perception. Taylor & Lederman (1975) have proposed a model of tactile roughness based on the static deformation of the skin touching regularly-grooved surfaces. The model used as a data base the results of experiments which implicated two major factors in the perception of roughness, viz., the width of the grooves (not the diameter of points of contact, as suggested by Cussler et al, 1977), and the normal finger forces applied (Lederman, 1974). These two experimental parameters similarly affected both perceived roughness and several aspects of skin deformation, i.e. the depth to which the skin penetrates a groove, the cross-sectional area of the finger within a groove (summed across the finger), and the cross-sectional area of the deviation of the skin from its resting position (summed across the entire finger). Because the last deformation parameter also qualitatively predicted the more subtle interactions in the data, it was "...tentatively preferred as the 'stimulus' for roughness".

Dynamic aspects of skin deformation were not considered in this model because of the relatively minor effect of a 25-fold alteration in hand speed (Lederman, 1974, Expt. II). However, the current studies suggest our model must be

extended to include the effects of one dynamic aspect of the touching process, i.e., shear. This factor was neither altered in the earlier experimental studies, nor considered in our original static model.

Returning to the heightened roughness phenomenon now, at least two other explanations of the paper effect seem intuitively plausible. The intermediate paper might serve as an amplifier, the edges catching on the surface irregularities, thereby producing travelling waves which add their effects to the vibratory signal directly under the fingertips. Alternatively, the paper may serve as a low-pass filter, passing only energy in the low frequency range (involving the larger, more widely-spaced bumps). This last interpretation must also show that tactile roughness is dependent on frequency, an idea which has been challenged by Lederman & Taylor (1972) and Lederman (1974). However, the latter studies did not specifically deal with the effect on perceived roughness of the relative distribution of frequencies present. Such a factor may therefore play a role in the paper phenomenon, and is worth considering at greater length. The relative merits of both the amplifier and low-pass filter interpretations require further study.

It is not immediately evident why the psychophysical functions obtained in the three experiments differ in slope

and sometimes shape from those reported by Stevens & Harris (1962). In the Stevens & Harris experiments, plotting the magnitude estimates of the roughness of sandpaper on log-log coordinates yielded straight line (power) functions with slopes of about 1.5. None of the present functions has a slope as steep as 1.5, and the functions in Fig. 3 are not even straight lines. Although such differences are not of immediate concern here, they are worth considering since they may indicate something about tactile roughness perception. One reason for the difference in slopes may be that roughness is not a function of a single physical dimension. There are numerous differences among the various surfaces used by Stevens & Harris and myself, e.g. uncovered vs paper-covered sandpaper, sandpaper vs beads, etc. Given such differences and the likelihood of there occurring irregularities in the curves due to stimulus anomalies, possible changes in slope and shape are entirely conceivable.

The psychophysical data reported in this paper do not tell us whether a thin hand-covering affects roughness discrimination as well as the magnitude of sensation. Such information is not typically obtained from psychophysical functions for prothetic continua. More often, the exponents of such power functions have been used to evaluate the rate of growth of sensation magnitude. We are thus currently

using a signal detection paradigm to determine the effect of the paper on roughness discrimination. Should the paper enhance discrimination, it may also facilitate tactile map reading. Tactile maps are raised, coded spatial representations which are used by the blind to move about their environment (e.g. streets, shopping centres, railway stations, etc.) unaided, and to gain political and geographical information about the world.

References

Cussler, E.L., Zlotnick, S.J. & Shaw, M.C. Texture perceived with the fingers. Perception & Psychophysics, 1977, 21, 504-512.

Gordon, I.E. Personal communication, October, 1976.

Gordon, I.E. & Cooper, C. Improving one's touch. Nature, 1975, 256, 203-204.

Lederman, S.J. Tactile roughness of grooved surfaces: The touching process and effects of macro- and microsurface structure. Perception & Psychophysics, 1974, 16, 385-395.

Lederman, S.J. Heightening impressions of tactile texture. In G. Gordon (Ed.) Active touch: the mechanism of recognition of objects by manipulation. An interdisciplinary approach. Oxford: Pergamon Press, 1978.

Lederman, S.J. & Taylor, M.M. Fingertip force, surface geometry, and the perception of roughness by active touch. Perception & Psychophysics, 1972, 12, 401-408.

Stevens, S.S. & Harris, J. The scaling of roughness and smoothness. Journal of Experimental Psychology, 1962, 64, 489-494.

Talbot, W.H., Darian-Smith, I., Kornhuber, H.H. & Mountcastle, V.B. The sense of flutter-vibration: comparison of the human capacity with response patterns of mechanoreceptive afferents from the monkey hand. Journal of Neurophysiology,

1968, _31_, 301-334.

Taylor, M.M. & Lederman, S.J. Tactile roughness of grooved surfaces: a model and the effect of friction. _Perception & Psychophysics_, 1975, _17_, 23-36.

Vallbo, A. & Johansson, R. The tactile sensory innervation of the human hand. In G. Gordon (Ed.) _Active touch: the mechanism of recognition of objects by manipulation. An interdisciplinary approach_. Oxford: Pergamon Press, 1978.

Footnotes

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1. I would like to thank Flex O Lite of Canada for generously donating the glass beads. I am also grateful for the assistance of Dr. J. Brown of the Mining department, and of F. M. Marchetti, L. Baxter and D. Kinch of the Psychology department at Queen's. Finally, I should like to thank Drs. Z. Jacobson and B. Green for their helpful comments.

2. The relative shear forces were calculated in the following manner. A piece of glass was mounted at the end of the balance arm of the force-control apparatus used in Expt. 2. The 425 μ stimulus surface used in the high shear condition was placed on a bed of beads, to permit it to slide freely along the glass. A thin length of thread was attached to one side of the stimulus surface so that it extended over the edge of the glass and down to a small container, to which it was attached. The weights on the force-control apparatus were adjusted so that an observer exerted approximately 120 gm with her middle finger normal to the stimulus surface. Small fishing weights were added to the container, one or two at a time. In this way, we could determine the shear force just required to move the surface under the finger when a 120 gm force was exerted normal to that surface. This method of determining relative shear was repeated

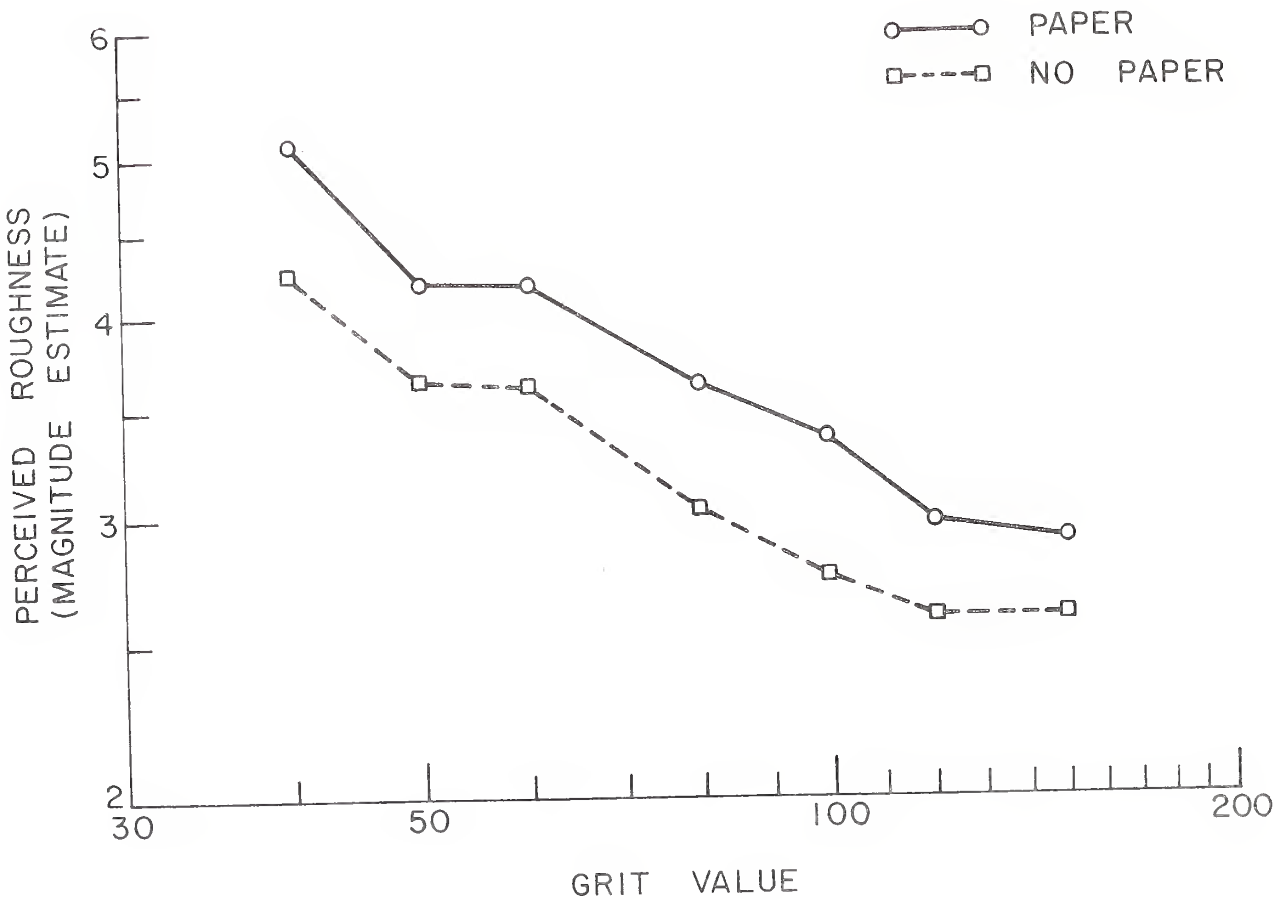
for the low and medium shear conditions using the corresponding stimulus surfaces (fixed beads for medium; rolling beads for low) with the appropriate papers placed between skin and surface. The average (of five measurements) shear forces determined were 0, 39 and 80 gm for the low, medium and high shear conditions, respectively.

Figure Captions

Figure 1. Perceived roughness (magnitude estimates) as a function of sandpaper grit in paper and no-paper conditions. Each point is based on 50 observations.

Figure 2. Perceived roughness (magnitude estimates) as a function of sandpaper grit in paper and no-paper conditions. a light force condition; b medium force condition; c heavy force condition. Each point is based on 60 observations.

Figure 3. Perceived roughness (magitude estimates) as a function of nominal width of sieve aperture and shear. Each point is based on 70 observations.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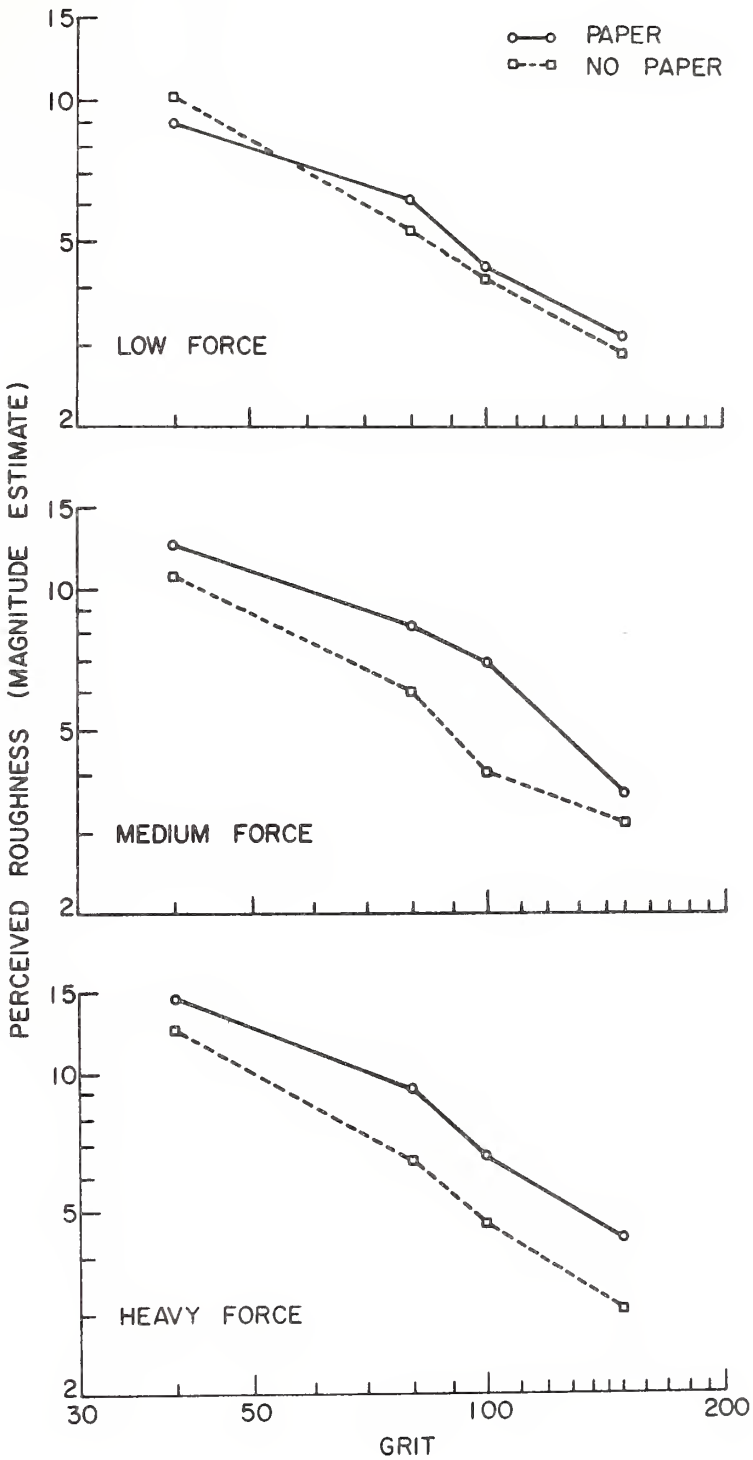
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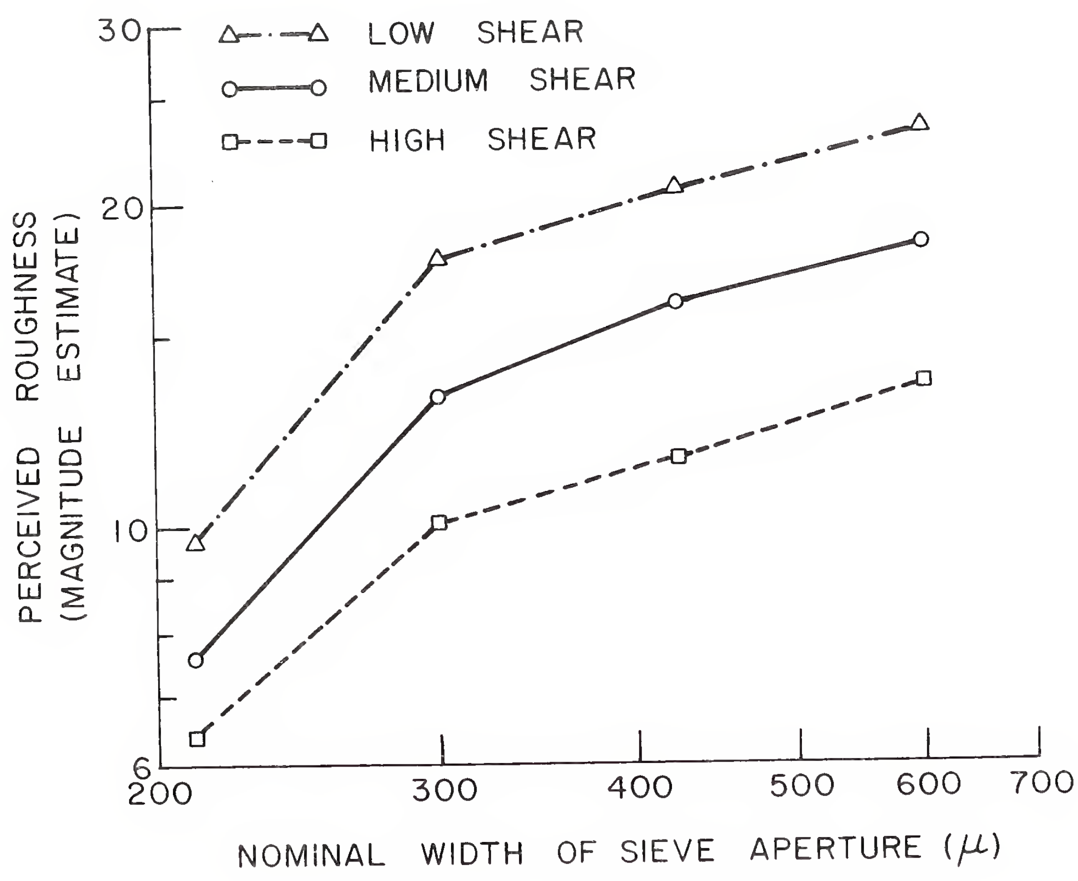
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